Polarimetric rainfall retrieval in a tropical environment: consistency analysis for two C-band radars in the Philippines

Irene Crisologo[1], Maik Heistermann[2], and Gianfranco Vulpiani[3]

[1]*University of the Philippines, Diliman, Quezon City, 1101 Philippines*
[2]*University of Potsdam,Institute of Earth and Environmental Sciences, Germany*
[3]*Presidency of the Council of Ministers, Civil Protection Department, Rome, Italy*

Irene Crisologo

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1 Introduction

The Philippine Atmospheric, Geophysical, and Astronomical Services Administration (PAGASA) has recently established a network of eight weather radars, which allows for high resolution monitoring of weather disturbances, the most common of which regularly affecting the country are tropical cyclones, sustained monsoon rains, and thunderstorms. Of the eight radars in the network, two are dual-polarized C-band radars. Polarimetric rainfall retrieval provides new opportunities for using C-band weather radars in tropical environments. In particular, they allow addressing the issue of path-integrated attenuation which is a dominant phenomenon for C-band radars that observe highly intensive tropical rainfall events.

The two radars used in this study have been observed to underestimate rainfall when compared to rain gages, which is attributed to miscalibration in the radar hardware. However, manually calibrating the radar hardware is a limitation at this point, due to having no access to the radars itself. Fortunately, self-calibration through polarimetric data processing is possible (Gorgucci, 1999)(Smyth, 1999)(Gourley, 2009). This procedure is applied to both polarimetric radars in the Philippine Radar network – the Tagaytay radar and Cebu radar.

Following the calibration through self-consistency approach, multiple rainfall retrieval methods using polarimetric techniques are implemented. First is by using only a simple Z-R relation to estimate rainfall from reflectivity. The second approach is using the specific differential phase (K_{DP}) reconstructed from the differential propagation phase (Φ_{DP}) to calculate the path-integrated attenuation (Bringi et al.,1990). The attenuation-corrected reflectivity is then used to estimate rainfall. Third is by using the reconstructed K_{DP} to directly estimate rainfall (Ryzhkov et al., 2005). Lastly, the use of both reflectivity and K_{DP} in a weighted combination for rainfall estimate was used. All methods have been implemented in the Open Source radar processing library *wradlib* (Heistermann et al., 2013b).

The focus of this study is to compare the different rainfall retrieval techniques as applied to the two C-band radars: The Tagaytay C-band radar situated in Southern Luzon and the Cebu C-band radar located in Central Visayas (Figure 1). The analysis will be based on two major events witnessed by each of the radars: Typhoon Kai-tak (local name *Helen*) which passed by the Philippines between August 12-18, 2012 for the Tagaytay C-band and Typhoon Son-tinh (local name *Ofel*) for the Mactan C-band radar which crossed the Philippines between October 21-29, 2012. By indentifying common strengths and weaknesses of the implemented retrieval methods for the two radars, we aim to support the development towards a joint retrieval approach for the PAGASA C-band radars.

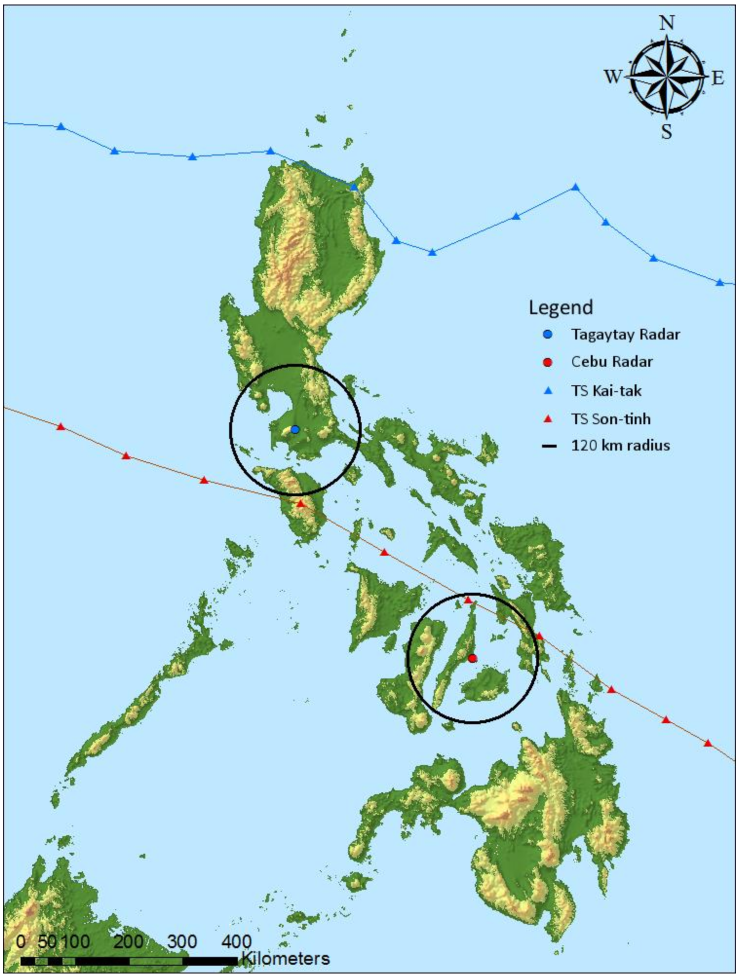

Figure 1. The location of the Tagaytay and Cebu C-band radars and the typhoon tracks of TS Kai-tak and TS Son-tinh that passed by the Philippines on August 2012 and October 2012, respectively.

2 Methodology

Rain gage observations for the Tagaytay and Cebu radars showing major underestimation of rainfall reveal that there is hardware miscalibration to be dealt with. Before going into the different rainfall retrieval methods, a polarimetric approach in calibration is applied for both radars.

2.1 Radar data

The two C-band radars in the Philippine radar network are located in Tagaytay, Batangas (TAG) and in Mactan, Cebu (CEB). Technical specifications of the two radars are listed in Table 1.

Table 1. Technical specifications of the two dual-polarization C-band radars in the Philippines.

	Tagaytay Radar	**Cebu Radar**
Bandwidth	C-band	C-band
Polarization	Dual-Pol	Dual-pol
Position (lat/lon)	14.142°N 121.022°E	10.322°N 123.980°E
Altitude (mamsl)	752	26
Maximum Range	120 km	120 km
Azimuth resolution	1°	1°
Gate length	500 m	500 m
Number of elevation angles	14	14
Elevation angles	0.5°, 1.5°, 2.4°, 3.4°, 4.3°, 5.3°, 6.2°, 7.5°, 8.7°, 10°, 12°, 14°, 16.7°, 19.5°	0.5°, 1.5°, 2.4°, 3.4°, 4.3°, 5.3°, 6.2°, 7.5°, 8.7°, 10°, 12°, 14°, 16.7°, 19.5°
Volume cycle interval	15 minutes	9 minutes

2.2 Radar data processing

The processing of radar data was implemented utilizing the Python package *wradlib*. *wradlib* is an Open Source library composed of tools that allow weather radar data processing. In this section we briefly discuss the methods that were used to derive the different rainfall products. For a more detailed description of the methods please refer to the library reference in http://wradlib.bitbucket.org.

2.2.1 Detection and removal of non-meteorological echoes

Clutter detection and removal for both radars were based on the fuzzy echo classification procedure from Vulpiani et al. (2012), implemented in the *wradlib* function *clutter.classify_echo_fuzzy*.

2.2.2 Differential Phase Processing

The study followed the differential propagation phase (Φ_{DP}) processing steps suggested by Vulpiani et al (2012). The first step is phase unfolding, where values that exceed the maximum unambiguous range are re-mapped and the offset is removed. This procedure has been implemented in the *wradlib* function *dp.process_raw_phidp_vulpiani.* After clutter correction, the initial estimation of K_{DP} is done by applying a convolution filter to Φ_{DP} with a window size of three gates.

2.2.3 Self-consistency approach in radar calibration

Observations from rain gages indicate that both Tagaytay and Cebu C-band radars suffer from hardware miscalibration, resulting in underestimation of when using reflectivity (Z_H) when calculating rainfall. To correct the underestimation of Z_H, a self-consistency approach was taken. The idea is that theoretical K_{DP}* can be computed from Z_H and Z_{DR}, using the equation suggested by Gorgucci et al. (1999):

$$K_{DP}^{*} = 1.46 \cdot 10^{-4} \cdot Z_H^{0.98} \cdot 10^{-0.2 \cdot Z_{DR}} \qquad (2.1)$$

This way, the theoretical K_{DP}* and observed K_{DP} can be compared to measure the amount of miscalibration of Z_H. In order to ensure that only Z_H is causing the underestimation, Z_{DR} is recalibrated. This is done by analyzing clutter-corrected data from 24 hours of light to moderate rainfall conditions at a 1.5° elevation angle. The Z_{DR} bias is calculated to be the mean of all Z_{DR} values for the analysis period, as shown in Figure 2. The Z_{DR} values used in Equation 2.1 are corrected for bias.

2.2.4 Rainfall retrieval

Here we briefly describe the different rainfall retrieval methods using polarimetric data from the radars. The different rainfall products are then compared for both radars.

a. R(Z) – *Rainfall from reflectivity*

The bias-corrected reflectivity Z (dBZ) is converted to rainfall rate R (mm/hr) using the Z-R relation for tropical rainfall suggested by the United States National Oceanic and Atmospheric Administration (NOAA) – $Z = 250 * R^{1.2}$.

b. R(Z+PIA) – *Rainfall from reflectivity after correcting for path-integrated attenuation*

Bringi et al. (1990) showed that the specific differential phase K_{DP} (*deg*) is almost linearly related by coefficient γ_{hh} *(dB deg*$^{-1}$*)* to the specific attenuation α_{hh} *(dB km*$^{-1}$*)* by:

$$\alpha_{hh} = \gamma_{hh} K_{DP} \qquad (2.2)$$

Integrating the specific attenuation along each beam gives the path-integrated attenuation, which is added to the measured reflectivity to get the corrected reflectivity. The corrected reflectivity is then converted to rainfall rate following the procedure in (a).

c. R(K_{DP}) – *Rainfall from specific differential phase*

Rainfall rate can also be estimated directly from K_{DP}, using the general expression suggested by Ryzhkov et al. (2005):

$$R = 129(|K_{DP}| / f)^{0.85} sign(K_{DP}) \qquad (2.3)$$

d. R(Z,KDP) – Rainfall from a weighted combination of Z and K_{DP}

Vulpiani and Baldini (2013) suggested a method that uses a weighted combination of R(Z) and R(K_{DP}):

$$R = w \cdot R(K_{DP}) + (1-w) \cdot R(Z) \text{ with } w = \begin{cases} 0 & \text{for } K_{DP} \le 0.5 \\ 2 \cdot K_{DP} - 1 & \text{for } 0.5 < K_{DP} < 1 \\ 1 & \text{for } K_{DP} \ge 1 \end{cases} \quad (2.4)$$

3 Results and Discussion

3.1 Self-consistency approach in calibration

The Z_{DR} bias was first calculated by taking the mean of the observed Z_{DR} values during periods of light rain (August 1, 2012 for the Tagaytay radar and November 7, 2013 for the Cebu radar), under the assumption that unbiased Z_{DR} would be almost zero in these conditions. For the Tagaytay radar, the histogram of the filtered Z_{DR} values is shown in Figure 2a, with a mean of 1.14 dB. The Z_{DR} histogram for the Cebu radar is shown in Figure 2b, with a mean of 1.85. This shows that the Cebu radar provides slightly more biased polarimetric values in terms of Z_{DR}. This is important to note if this variable is to be used for other purposes such as rainfall estimation.

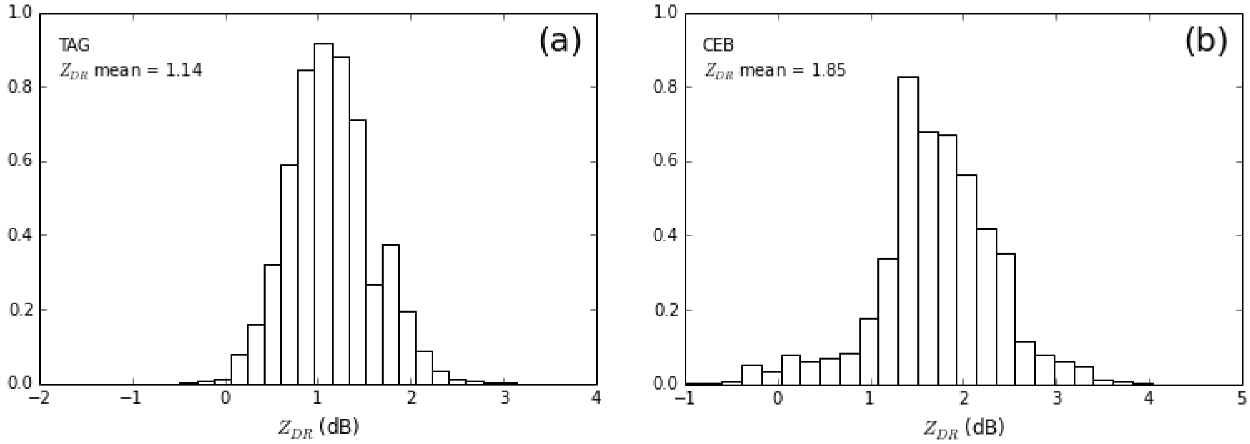

Figure 2. Histogram of Z_{DR} values for the (a) Tagaytay Radar on August 1, 2012 with 1.5° elevation angle and (b) Cebu Radar on November 7, 2013 with 1.5° elevation angle. The mean Z_{DR} values for the Tagaytay radar and Cebu radar are 1.14 and 1.85, respectively.

After correcting for these biases in Z_{DR}, the reflectivity Z_H is then calibrated. This is done by comparing the observed specific differential phase K_{DP} (estimated from observed Φ_{DP}) and calculated specific differential phase K^*_{DP} based on Equation 2.1, and fitting a regression line of the scatter plot that passes through the origin (Figure 3). The inverse of the slope is the Z_H bias. The corrected Z_H values were then used as inputs to the rainfall retrieval methods.

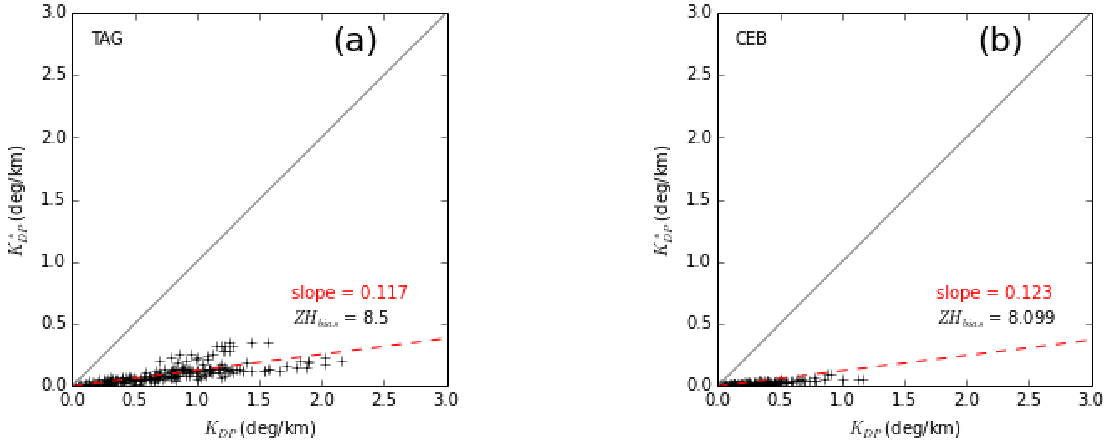

Figure 3. Scatter plot of the theoretical specific differential phase (K^*_{DP}) and observed specific differential phase (K_{DP}). Both radars experience severe systematic miscalibration where the systematic bias is 8.5 dBZ and 8.099 dBZ for the Tagaytay and Cebu radars, respectively.

3.2 Rainfall retrieval

Typically, rain gage networks are used to verify radar rainfall estimates. While there are several rain gages available within the coverage of the Tagaytay radar, the absence of rain gages within the Cebu radar coverage makes it difficult to do gage validation. Instead, accumulation maps for the Typhoon events are used to compare the different rainfall-retrieval methods. For the Tagaytay radar, accumulation maps are shown in Figure 4, for a four-day period from August 15-18, 2012. This was when Typhoon Kai-tak was passing north of the Philippines. The accumulation maps for the Cebu radar are shown in Figure 5, for the four-day period of October 22-25, 2012. Typhoon Son-tinh passed across the central Philippines, crossing the radar within this time period.

The four rainfall retrieval methods show similar spatial distribution of the rainfall for the Tagaytay radar. The rainfall accumulation using R(Z) product is significantly lower than all the other products, where the the maximum rains appear to have fallen at the southern portion of Manila, receiving an estimate of only about 220 mm within a four-day period. This is associated with the strong attenuation effects experienced by C-band radars. Correcting for this attenuation greatly improves the rainfall estimation, most notably over the island province of Mindoro, as seen from the accumulation map of R(Z+PIA). Here the amount of rainfall that the western part of Mindoro received increased from below 100 mm to more than 200 mm. The use of K_{DP} in rainfall retrieval looks slightly different than the other products, having an increased value of rainfall estimates near the radar station. The combination of R(Z,K_{DP}) provides a more probable rainfall distribution, with R(Z+PIA) having a more dominant contribution. However, areas of heavier rainfall are more influenced by the R(K_{DP}) product. With R(Z) having a more pronounced underestimation that spans the entire radar field, rainfall estimation by the Tagaytay radar is possible only by using polarimetric rainfall retrieval methods.

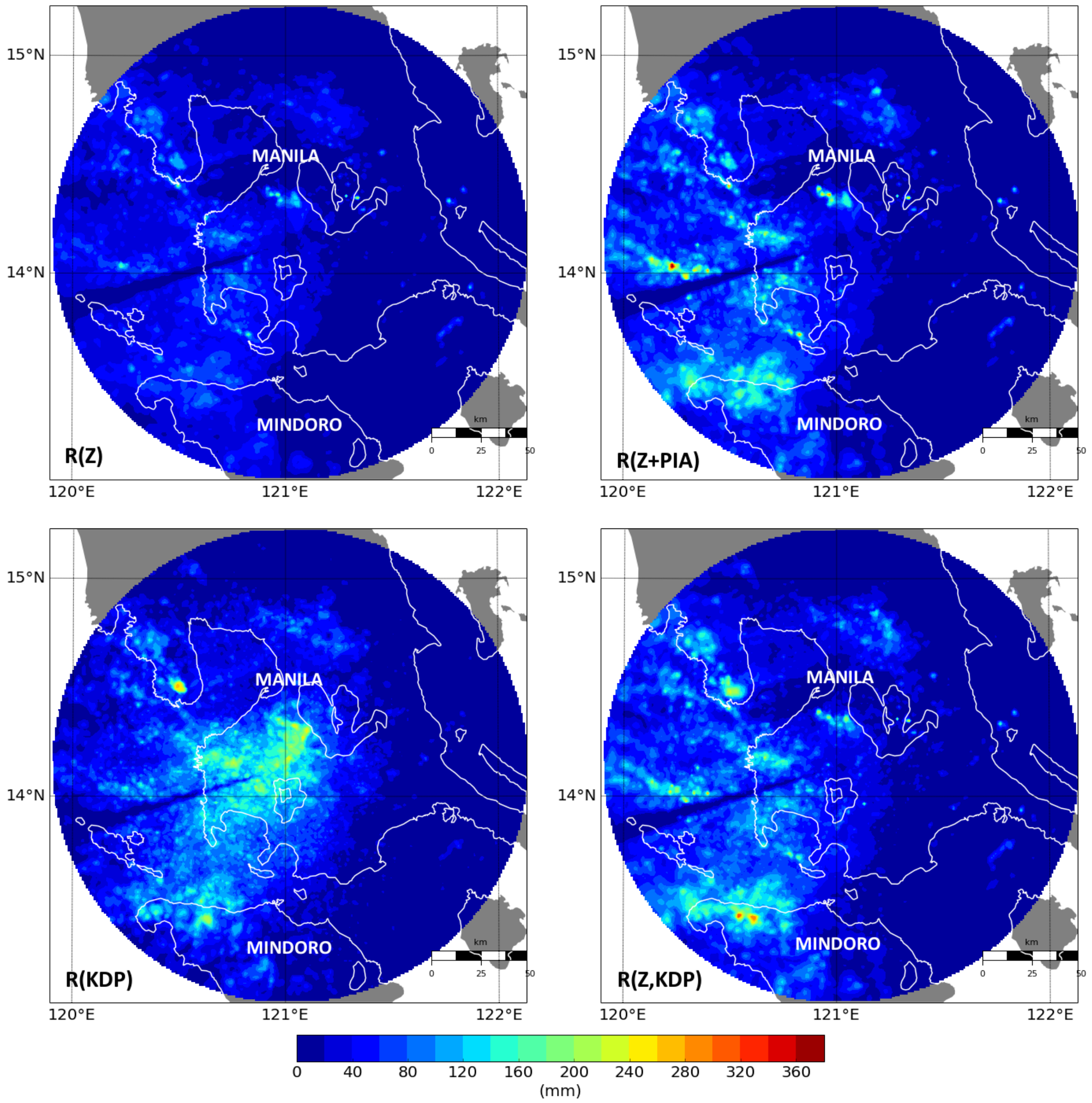

Figure 4. Rainfall accumulation maps based different radar-rainfall retrieval methods for the Tagaytay radar for August 15-18, 2012 when Typhoon Kai-tak passed by north of the island of Luzon, Philippines.

The comparisons of the different products used for the Cebu radar are similar, with R(Z) having the lowest estimates among all the products. The attenuation-corrected reflectivity R(Z+PIA) estimates show a high amount of rainfall at the eastern portion, where the eye of the typhoon passed over the province of Leyte. $R(K_{DP})$ estimates captures the high rainfall over the western portion of the Bohol island provice, but for some areas its estimates are lower than the R(Z+PIA) estimates. The $R(Z,K_{DP})$ estimates show a more plausible distribution, capturing all the areas with high rainfall (western Bohol and Leyte). Similar to the Tagaytay radar, with the reflectivity-based rainfall estimation having a systematic underestimation, the Cebu radar requires the use of polarimetric rainfall retrieval methods to achieve a more accurate estimate.

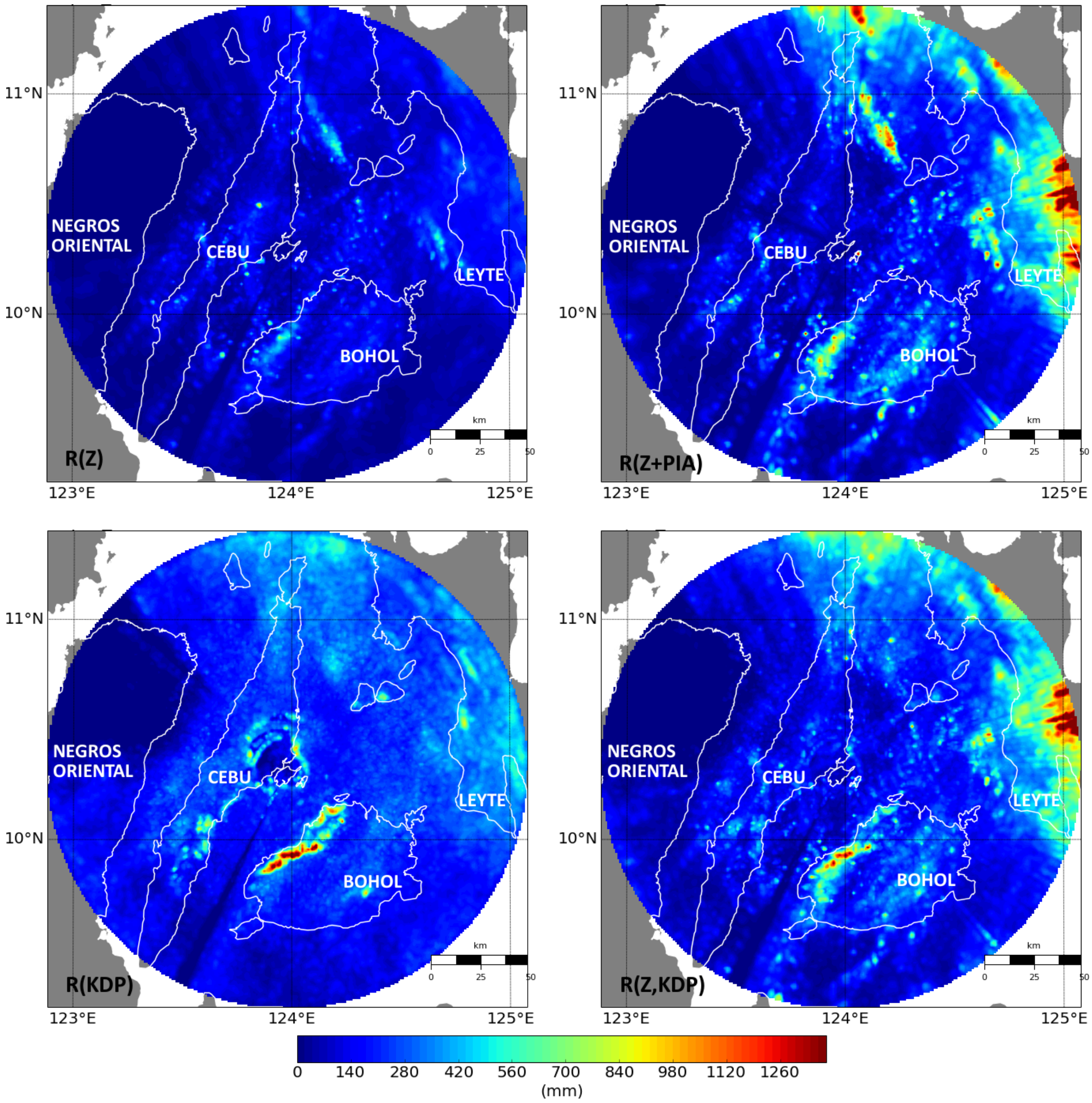

Figure 5. Rainfall accumulation maps based different radar-rainfall retrieval methods for the Tagaytay radar for October 22-25, 2012 when Typhoon Son-tinh passed across the Visayas islands.

4 Conclusion and outlook

In this study, we showed how the Philippine C-band radars in Tagaytay and Cebu are both experiencing severe reflectivity miscalibration. A self-consistency approach in calibration using polarimetric techniques was applied for both radars.

For both the dual-polarization C-Band radars in Tagaytay and Cebu, rainfall estimation is only plausible using polarimetric rainfall retrieval methods. Reflectivity-based estimates show a systematic underestimation of a comparable degree for both radars, at 8.5 dBZ and 8.099 dBZ for the Tagaytay and Cebu radars, respectively. One Typhoon event for each of the radars was used as a case study – Typhoon Kai-tak for the Tagaytay radar and Typhoon Son-tinh for the Cebu radar. All processing methods were done using the tools available from the open source radar processing library *wradlib*. Further verification using rain gages is recommended.

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